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Generation of water-in-oil and oil-in-water microdroplets in polyester-toner microfluidic devices

Evandro Piccin [a,*], Davide Ferraro [b], Paolo Sartori [b], Enrico Chiarello [b], Matteo Pierno [b], Giampaolo Mistura [b,**]

[a] Departamento de Química, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil
[b] CNISM and Dipartimento di Fisica e Astronomia G. Galilei, Università degli Studi di Padova, Padova, Italy

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ABSTRACT

This paper demonstrates that disposable polyester-toner microfluidic devices are suitable to produce either water-in-oil (W/O) or oil-in-water (O/W) droplets without using any surface treatment of the microchannels walls. Highly monodisperse W/O and O/W emulsions were generated in T-junction microdevices by simply adding appropriate surfactants to the continuous phase. The dispersion in size of droplets generated at frequencies up to 500 Hz was always less than about 2% over time intervals of a couple of hours.

1. Introduction

Droplet-based microfluidics is an active research field that presents great potential for high-throughput chemical and biological analysis, synthesis of advanced materials, sample pretreatment, protein crystallization and encapsulation of cells [1–4]. In these devices, droplets of a fluid forming the so-called dispersed phase are carried by the stream of a second immiscible fluid identified as the continuous phase. Depending on the application, two major types of droplets are usually produced: water-in-oil (W/O) or oil-in-water (O/W) droplets.

The generation of stable droplets depends, among other things, on the wettability of the channel walls. The continuous phase should completely wet the channel walls, while the degree of wetting by the dispersed phase should be very low. Oils preferentially wet hydrophobic surfaces, whereas aqueous solutions preferentially wet hydrophilic surfaces. Thus, W/O droplets are usually produced in hydrophobic microchannels and O/W droplets are commonly generated in hydrophilic devices. Most published studies involve the production of W/O droplets because the majority of biological and chemical reactions occur in an aqueous solution [5–8]. This significantly simplifies the fabrication of microfluidic devices because it requires hydrophobic walls, a feature guaranteed by the use of common polymers. These include polydimethylsiloxane (PDMS) [9,10] and poly(methylmethacrylate) (PMMA) [11,12]. However, when O/W droplets are needed, the polymeric channel walls must be turned hydrophilic. Over the past few years various methodologies [6,7,13–15] have been devised to accomplish this task, which are usually technically demanding and time consuming. An alternative way consists in the addition of suitable surfactants to the continuous phase [5,16].

The direct-printing technology for fabricating toner-based microfluidic devices was first proposed by do Lago et al. [17]. In this technique, the device layout is laser-printed on two sheets of polyester film that are then sealed together by thermal lamination for creating the channels. The toner printing acts as a glue in the lamination process. The depth of the channels (~12 μm) was determined by the height of the two toner layers that are laminated together. More recently, this fabrication process was modified in order to produce multilayered polyester-toner devices with larger channel depths [18]. In this latest methodology, the microchannels are made by cutting a polyester sheet containing uniform layers of toner. This cut-through sheet is sandwiched between

* Corresponding author at: Departamento de Química, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, Pampulha, Belo Horizonte, MG, Brazil. Tel.: +55 31 3409 6389.
** Corresponding author at: Dipartimento di Fisica e Astronomia G. Galilei, Università degli Studi di Padova, Via F. Marzolo 8, 35131 Padova, Italy. Tel.: +39 049 827 7020.
E-mail addresses: evandrop@ufmg.br (E. Piccin), giampaolo.mistura@unipd.it (G. Mistura).

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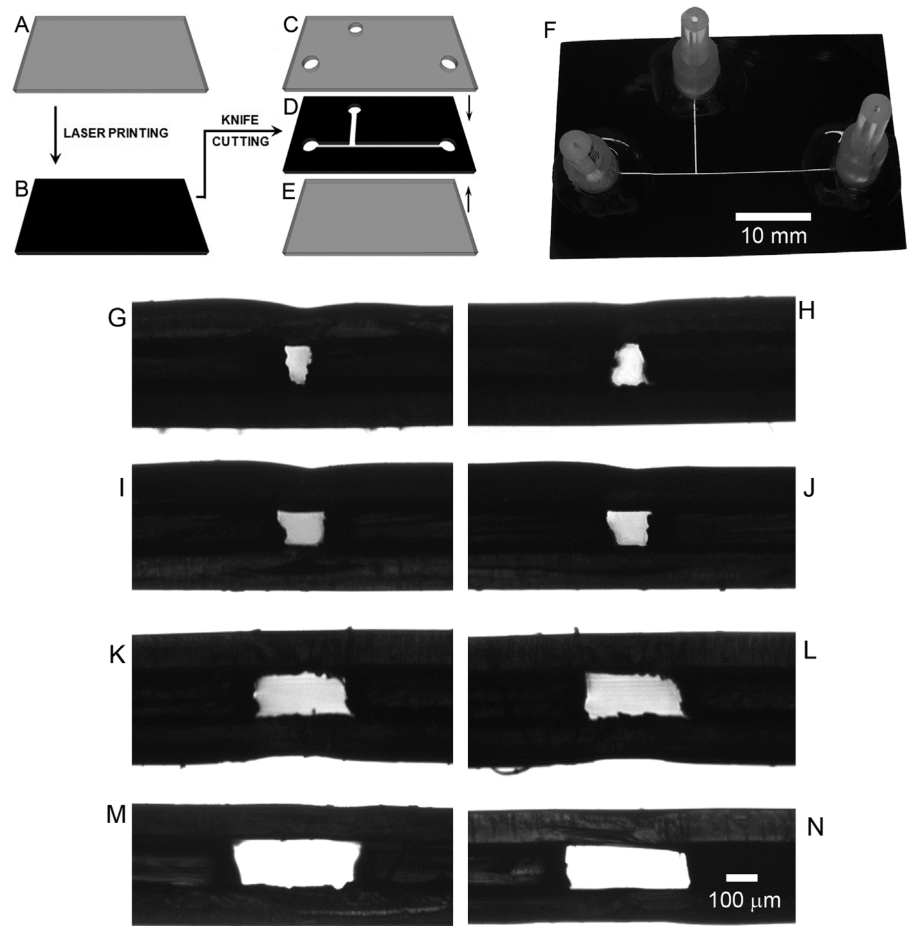

Fig. 1. Schematic diagram showing the main steps of the fabrication process: (A) polyester film, (B) polyester film toner-printed on both sides, (C) polyester film with perforated access holes, (D) microchannels cut on the printed polyester, (E) polyester film used for sealing. (F) Full view photograph of the T-junction microfluidic device constructed in PeT and utilized for the generation of W/O and O/W droplets. (G–N) Photographs of the cross-section of microchannels of different sizes. Each image refers to a different PeT chip. Characteristic widths: (G and H) 60 μm; (I and J) 90 μm; (K and L) 250 μm; (M and N) 350 μm.

uncoated polyester sheets containing precut access holes. Thus, the depth of the channels is determined by the number and the thickness of the middle cut-through sheets and the toner layers. When compared to other rapid prototyping techniques, the toner-based technology presents some advantages owing to its very short fabrication time, independence of clean room facilities and low cost (~$0.15 per device) [19]. Polyester-toner (PeT) devices have found widespread applications in many areas including clinical bioassays [19], microchip electrophoresis [20], DNA extraction and PCR amplification [18], and DNA analysis [21]. However, all of these applications were developed for conventional continuous flow systems and, considering the increasing demand for droplets based devices [1,2], it would be important to merge these two technologies.

In the following, we will present T-junctions made in PeT where the two immiscible liquids flow through two orthogonal channels and form droplets when they meet [22] (see Fig. 1). The droplets generated in this way are highly monodisperse and are separated by an equal spacing [1–4]. It will be demonstrated that these disposable PeT devices can be used for generating W/O and O/W droplets without any surface modification of the microchannels. Stable W/O droplets were obtained using hexadecane or mineral oil as continuous phases with the addition of Span 80, while O/W droplets were generated using aqueous solution with Triton X-100 as continuous phases and hexadecane or mineral oil as dispersed phases. Surfactants were added to the continuous phase to lower the interfacial energy, that is to facilitate the formation of new interfaces and to stabilize the formed emulsion droplets from coalescence during their motion [4,16].

2. Materials and methods

2.1. Chemicals

All chemicals used were of analytical reagent grade quality and were employed as received. Hexadecane (CAS number: 544-76-3, viscosity ~3 cP, density ~0.77 g/cc), mineral oil (light) (CAS number: 8042-47-5, viscosity ~16 cP, density ~0.84 g/cc), Span® 80, and Triton™ X-100 were purchased from Sigma-Aldrich. Polyester sheets (transparency films, model CG3300) were acquired from 3 M. Distilled water was used in all experiments.

2.2. Fabrication procedure

The PeT microfluidic devices were fabricated by direct-printing combined with xurography [17,23–25]. The fabrication process was similar to previously reported methodologies [18,19]. Polyester sheets (A4 size, 100-μm-thick) were first printed twice on both sides using a laser printer (Hewlett-Packard model 4250) with 600-DPI resolution and equipped with a black toner cartridge (model Q5942A). This process yields two layers of toner printing on each side of the polyester film. The T-junction layout for the devices was drawn using the AutoCAD 2011 software and the microchannels